Appendix D: Flow Measurement Results of the Lower Delaware Monitoring Program

Todd W. Kratzer, P.E.

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Flow Monitoring

Associating water quality with flow is important for proper assessments of changes in water quality. A year with higher flows may have elevated pollutant loadings, presenting lower concentrations, thus showing a stable or better water quality when degradation may actually be occurring. The opposite may be true during lower flows. As pollution loadings increase beyond the receiving stream's dilution capacity, concentrations become elevated over a range of flows that would normally present lower concentrations. Flow data combined with water quality concentrations provides loading estimates over a range of flows. A loading estimate may reveal an increased pollution problem during higher flows that may have otherwise gone unnoticed if concentration was used as a sole indicator. Thus, loading provides an effective indicator for assessment and remediation of pollution impacts upon water quality.

River Flow Measurements

The Lower Delaware River, which extends from the southern terminus of the Middle Delaware National Scenic and Recreational River (Slateford, PA) to Trenton, NJ, has three calibrated U.S. Geological Survey (USGS) continuous flow monitoring stations: Belvidere bridge, Riegelsville bridge, and at the Calhoun Street Bridge at Trenton, NJ. Using these sites, and flow-measurement sites on the adjacent tributaries, flow was estimated for all of the water quality monitoring sites along the Lower Delaware River. **Table 1** shows the flow-estimation equations for the Lower Delaware River water quality monitoring sites. The equations use drainage-area weighting to interpolate or extrapolate flows for water quality monitoring sites that are not near the USGS flow-monitoring sites.

Table 1. Flow estimating equations for Delaware River monitoring sites, beginning at the most upstream site.

River Monitoring Site	River Mile	Drainage Area (mi^2)	Flow Estimating Equation[1]
Columbia/Portland Foot Bridge	207.40	4,165	Qport = Qbel – (Qbel * 0.048435)
Belvidere Bridge	197.84	4,377	Qbel = Qbel - (Qbel*0.034620)
Easton – Northampton St Bridge	183.82	4,717	Qnh = Qbel + [(Qrgl-Qbel)*0.110976]
Riegelsville Bridge	174.70	6,175	Qreg = Qreg
Milford – Upper Black Eddy Bridge	167.70	6,381	Qmil = Qtrent-[(Qtrent-Qrgl)*0.659504]
Frenchtown – Uhlerstown Bridge	164.30	6,408	Qfr = Qtrent-[(Qtrent-Qrgl)*0.614876]
Bulls Island – Lumberville foot bridge	155.40	6,598	Qbi = Qtrent-[(Qtrent-Qrgl)*0.300826]
Stockton Bridge	151.90	6,656	Qst = Qtrent-[(Qtrent-Qrgl)*0.204959]
Lambertville – New Hope Bridge	148.70	6,680	Qlam = Qtrent-[(Qtrent-Qrgl*0.165289]
Washington Crossing Bridge	141.80	6,735	Qwx = Qtrent-[(Qtrent-Qrgl)*0.074380]
Calhoun Street Bridge	134.34	6,780	Qtrent = Qtrent

[1] Delaware River flow estimate sites are represented as: Qport = flow at Portland; Qbel = flow at USGS gage at Belvidere; Qnh = flow at Northampton Street Bridge at Easton; Qrgl = flow at USGS gage at Riegelsville; Qmil = flow at Milford bridge; Qtrent = flow at USGS gage at Trenton (Calhoun Street Bridge); Qfr = flow at Frenchtown bridge; Qbi = flow at Bulls Island foot bridge; Qst = flow at Stockton bridge; Qlam = flow at Lambertville bridge; and Qwx = flow at Washington Crossing bridge.

Tributary Flow Measurements

Many of the tributaries to the Lower Delaware had not been monitored for flows prior to the initiation of the DRBC Lower Delaware Monitoring Program. There are several tributaries that are monitored for flow by the USGS, but these do not have continuous flow monitors near the confluence with the Delaware River where the DRBC water quality monitoring sites were located. The USGS gage on the Lehigh River was the exception since it had a flow-monitoring site very close to the mouth of the Lehigh River. Therefore, the DRBC implemented a flow-monitoring program for those tributaries that were being sampled for water quality. An association between flow and water surface elevation was calibrated for each tributary with several measurements over a range of flows. The measurement of the water surface elevation (stage measurement) was recorded to the nearest 0.01 feet and referenced to either a bridge datum or a staff gage. A flow versus stage association (calibration), known as a “rating” (created using linear regression), was established for each flow measurement site. The calibrated rating provided a direct relationship between stage and flow so that only stage measurements were needed each time a water quality sample was collected to associate the sample with the existing flow.

Some water quality monitoring sites were at or near a USGS flow and/or water quality monitoring site. Whenever possible, USGS flows were used to supplement the DRBC flow measurements, especially for the higher flows. Stage records (bridge or staff gages) were used to integrate DRBC and USGS flow-measurement data. Whenever available, the stage records presented a good relationship. The associated flows were then appended to both DRBC and USGS data sets to provide data for voids in the stage/flow rating curves. Continuous records for flow and stage data were available for Bushkill Creek from Lafayette College, thus allowing this same technique to be used to associate the Lafayette College flow estimates to the DRBC stage records.

Table 2 lists the streams that were monitored for water surface elevation and flow (cubic feet per second, cfs) at a reference datum (stage or gage reading, feet) that used either a marked in-stream staff gage (or rod) or a mark on a bridge deck (datum). Flow ratings should not be used for estimating stream flow beyond approximately 10 percent of the flow range used for the calibration.

Several tributaries in the Lower Delaware had unstable channels, requiring more flow measurements to maintain accuracy in the stage and discharge calibration. Tributaries exhibiting this characteristic were Martins Creek, Bush Kill, Nishisakawick Creek, Tohickon Creek, and Paunacussing Creek. Tohickon Creek flows that were measured by the DRBC near the mouth were compared to the USGS’s flow measurement station at Pipersville, Pa. Bush Kill flows measured by the DRBC were referenced to both a bridge datum and a flow measurement station near the mouth that was maintained by Lafayette College. Due to changes in the channel cross-section at the DRBC gage site from higher flows that reposition the unstable substrate, the relationship between the stage and flow changed frequently. The continuous water depth monitor, operated by Lafayette College was located at a stable channel site and was therefore used as the water stage reference.

Two streams that did not present a safe cross-section for flow measurements were Paulins Kill and the Musconetcong River. The Musconetcong stage and flow calibration could utilize recent instantaneous flow measurements by the New Jersey District of the U.S. Geological Survey at the DRBC water quality site, or from a USGS continuous flow monitoring site approximately 10 miles upstream (Bloomsbury, NJ). The Paulins Kill required flow measurements near its confluence with the Delaware River, which was a difficult site to access. This site was characterized by a substrate of large boulders situated in a deep channel. The U.S. Geological Survey may be contracted for these measurements if a good relationship cannot be obtained between the DRBC gage readings and the closest upstream USGS gage. If a good relationship exists between the gages, then drainage-area-weighting should provide good flow estimates for the DRBC water quality site.

Table 2. Lower Delaware tributary flow measurement sites and stage-flow relationships.

Stream	Drainage Area (mi^2)	Calibration Flow Range[1] (cfs)	Stage-Flow Equations
Paulins Kill	177.00	Entire Range	1.405 x USGS flow at Blairstown
Pequest River	157.00	146 – 354	Q = (-371.84 x Gage Ht) + 5,562.3
Martins Creek	44.50	(2002) 7.8 – 40.3 (2003) 30.4 – 123.2	<u>2002:</u> DRBC Gage > 9.18', Q = (-68.608 x Gage Ht) + 647.71 DRBC Gage ≤ 9.18', Q = (-191.17 x Gage Ht) + 1,774.1 <u>2003:</u> All DRBC Gage Ht, Q = (-281.19 x Gage Ht) + 2,634.9
Bushkill Creek	80.00	(2001-2002) 30.2 – 215 (2003) 42.2 - 403	Continuous Lafayette flow monitor <u>2001-2002:</u> Q = (-263.45 x Cemetery Road Gage Ht) + 4,621 <u>2003:</u> Q = (-309.56 x Cemetery Road Gage Ht) + 5,370.9
Lehigh River	1,361.00	Entire Range	1.004 x USGS flow at Glendon
Pohatcong Creek	57.10	5.40 – 116	Q = (-81.97 x Gage Ht) + 1,671.2
Musconetcong River	156.00	Entire Range	1.1064 x USGS flow at Bloomsbury
Cooks Creek	29.50	5.4 – 75.4	DRBC Gage > 16.83', Q = (-11.091 x Gage Ht) + 196.24 DRBC Gage ≤ 16.83', Q = (-76.392 x Gage Ht) + 1,297.3
Nishishakawick Creek	11.10	(2001-2002) 0.0 – 13.3 (2003) 3.0 – 32.5	<u>2001–2002:</u> DRBC Gage > 15.32', Q = (-1.7218 x Gage Ht) + 27.925 DRBC Gage ≤ 15.32', Q = (-34.838 x Gage Ht) + 535.38 <u>2003:</u> All DRBC Gage Ht, Q = (-32.604 x Gage Ht) + 523.89
Tinicum Creek	24.00	0.0 – 92.2	Q = (-34.458 x Rock Datum Gage) + 97.022
Tohickon Creek	112.00	3.8 – 59.2	DRBC Gage > 5.06', Q = (-31.947 x Gage Ht) + 172.43 DRBC Gage ≤ 5.06', Q = (-73.589 x Gage Ht) + 382.6
Paunacussing Creek	7.87	3.8 – 20.6	(-39.902 x Bridge Gage Ht) + 613.55
Lockatong Creek	23.20	0.0 – 28.3	DRBC Gage > 19.76', Q = (3×10^{72}) x $e^{(-8.4058 \times \text{Gage Ht})}$ DRBC Gage ≤ 19.76', Q = (-48.223 x Gage Ht) + 954.28
Wickecheoke Creek	26.60	0.4 – 53.8	DRBC Gage > 18.02', Q = (-7.7843 x Gage Ht) + 142.85 DRBC Gage ≤ 18.02', Q = (-38.331 x Gage Ht) + 693.43
Pidcock Creek	12.70	0.0 – 11.1	DRBC Gage > 15.86', Q = (-12.349 x Gage Ht) + 198.12 DRBC Gage ≤ 15.86', Q = (-39.247 x Gage Ht) + 624.77

[1] The measured flow range extended by ± 10 percent.

Figures 1-12 illustrate the stage and flow calibrations for several tributaries within the Lower Delaware River corridor, beginning at the most upstream site. Stage and flow calibrations (flow rating curve) should only be associated with the actual measured flow range. However, an extrapolation of the rating curve to ± ten percent of the measured flow range should maintain an acceptable accuracy. When two separate flow ranges were defined, then ± ten percent of each flow range was used for defining the maximum extent of each segment.

Most of the stage and discharge relationships indicated 2 distinct rating curves, one representing the higher flows and one representing the lower flows. **Figures 1c, 2, 5c, 6, 8, 10a, 11a, and 12** show dual stage and flow calibration curves for Pequest River, Martins Creek, Cooks Creek, Nishisakawick, Tohickon, Lockatong Creek, Wickecheoke Creek and Pidcock Creek, respectively. Dual rating curves are common for most streams in the Lower Delaware River. This effect may be due to the changes in cross-sectional area during low flows. Thalwegs present a modified cross-section, which usually is characterized by a minimal width-to-depth ratio than that of the normal channel. Therefore, changes in flow, conveyed in a thalweg, may represent greater changes in the associated water depth.

The following presents the stage and flow calibrations (ratings) that were established for selected tributaries within the Lower Delaware.

Pequest River

The Pequest River was monitored for flow at the Orchard Street Bridge by the DRBC. However, at the time of this report, only two flow measurements had been performed to calibrate the rating curve (**Figure 1a**). A USGS flow measurement site existed near the Market Street dam. However, these data could not be used to supplement the DRBC data since only two stage measurements were available to determine a relationship between the data sets (**Figure 1b**). If the USGS flow rating shows a good relationship to the DRBC rating then the USGS stage can be measured and directly associated with flows at the DRBC monitoring site. **Figure 1c** shows a good relationship between stage and flow for the USGS flow measurement site.

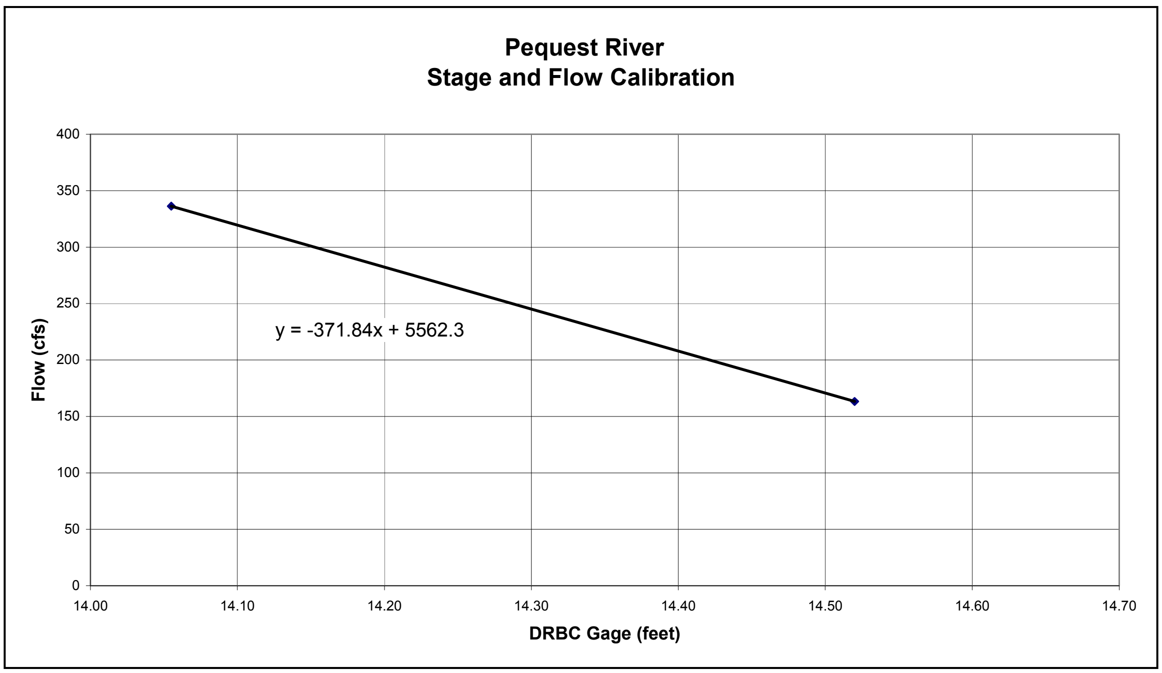

Figure 1a. DRBC stage and flow calibration for the Pequest River at river mile 197.8.

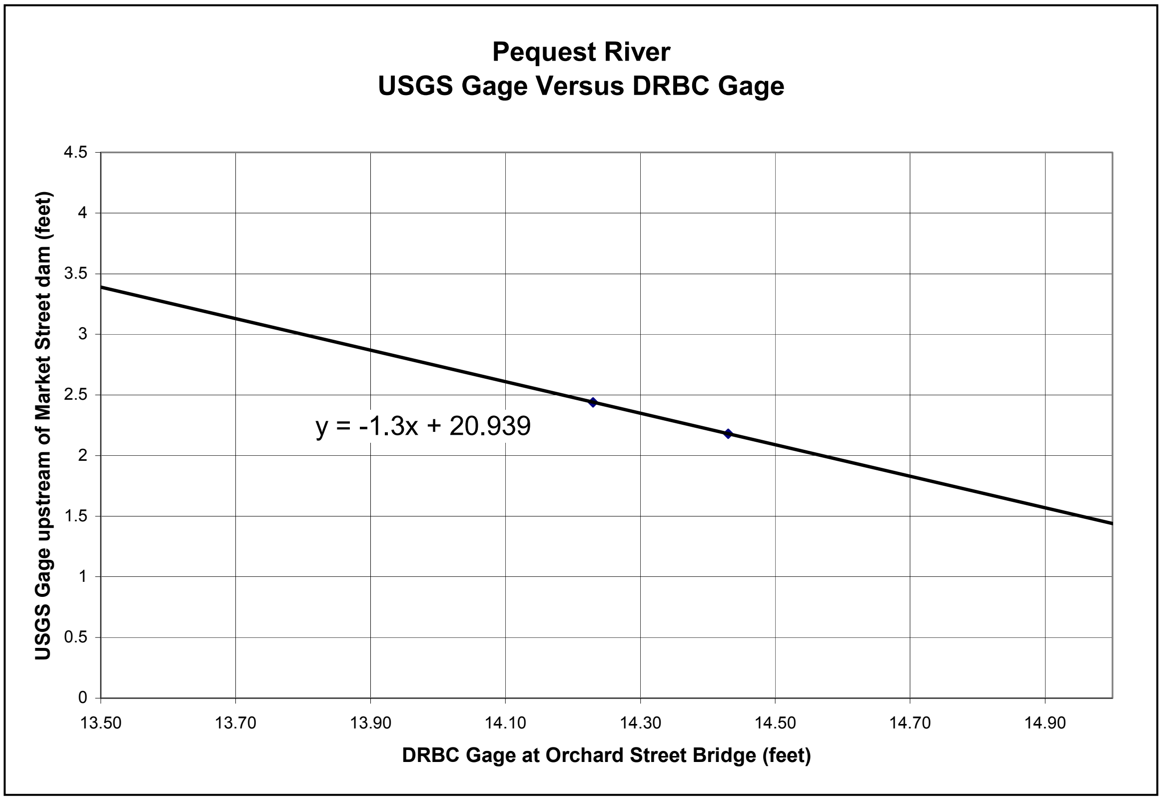

Figure 1b. USGS stage versus DRBC stage measurements for the Pequest River at river mile 197.8.

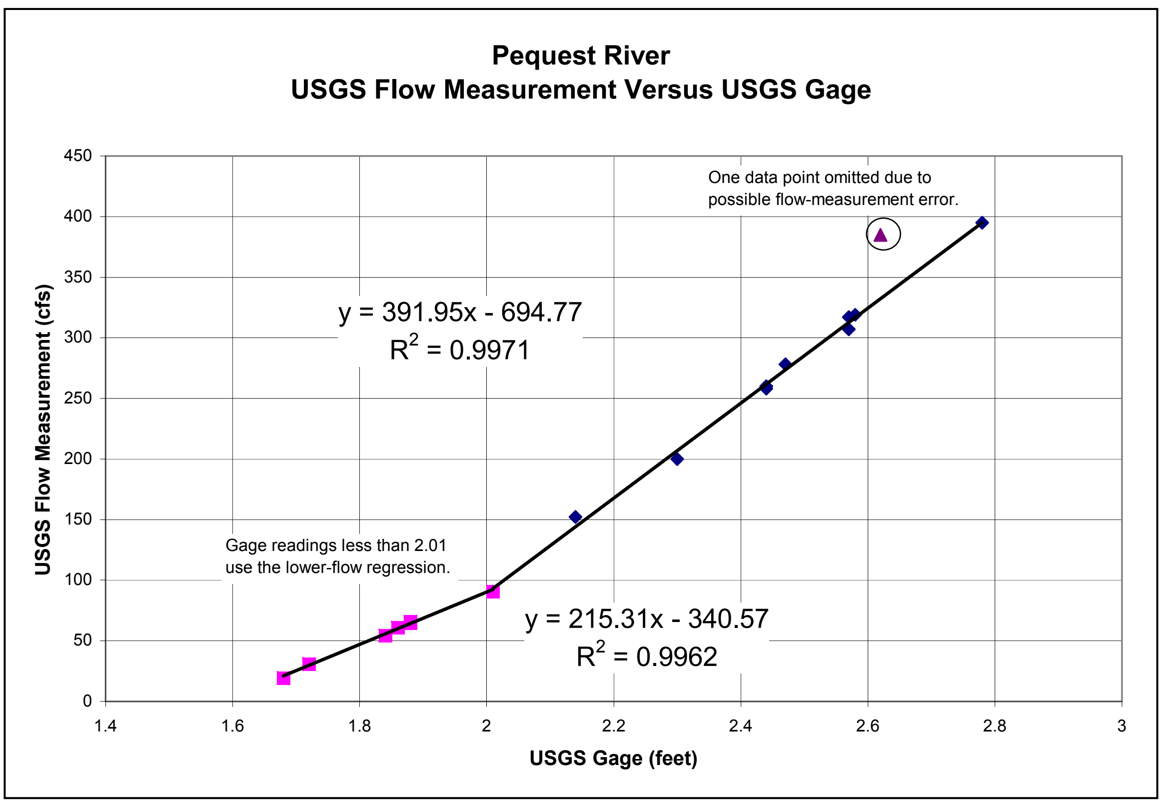

Figure 1c. USGS stage and flow calibration for Pequest River at river mile 197.8.

Martins Creek

Martins Creek presented two distinct rating curves: one for the 2002 and one for the 2003 data (**Figure 2**). The 2002 data showed a dual rating for higher and lower flows while the 2003 data showed a continuous relationship between higher and lower flows.

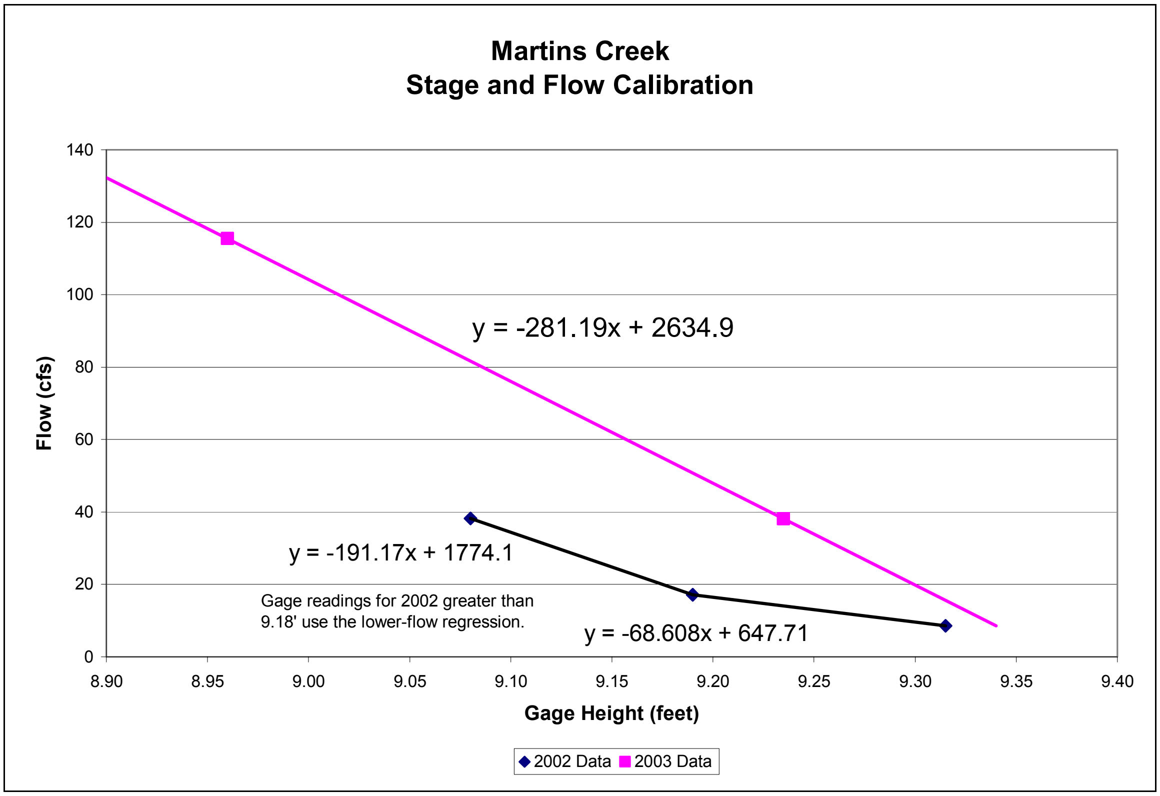

Figure 2. Stage and flow calibration for Martins Creek at river mile 190.58.

Bushkill Creek

Bushkill Creek flow measurements were performed at the Cemetery Road Bridge that is approximately 1.5 miles upstream from the mouth. **Figure 3a** shows the rating for the Cemetery Road bridge gage. This rating did not present a good relationship between the stage and flow. Continual scouring and deposition of unstable substrates at the bridge gage may have been the main cause of the shifting rating.

Concurrent with the DRBC Lower Delaware study, Lafayette College has conducted a water quality monitoring program. Lafayette College uses a continuous recording pressure transducer to measure the water depth (stage) at a site near the mouth of the Bush Kill. The stage had a good flow relationship and this flow was compared to the DRBC gage readings at the Cemetery Bridge that corresponded to the same date and time. This rating is presented in **Figure 3b**. The rating showed two distinct relationships between stage and flow for the combined data set of 2001 and 2002 and another rating for the 2003 data.

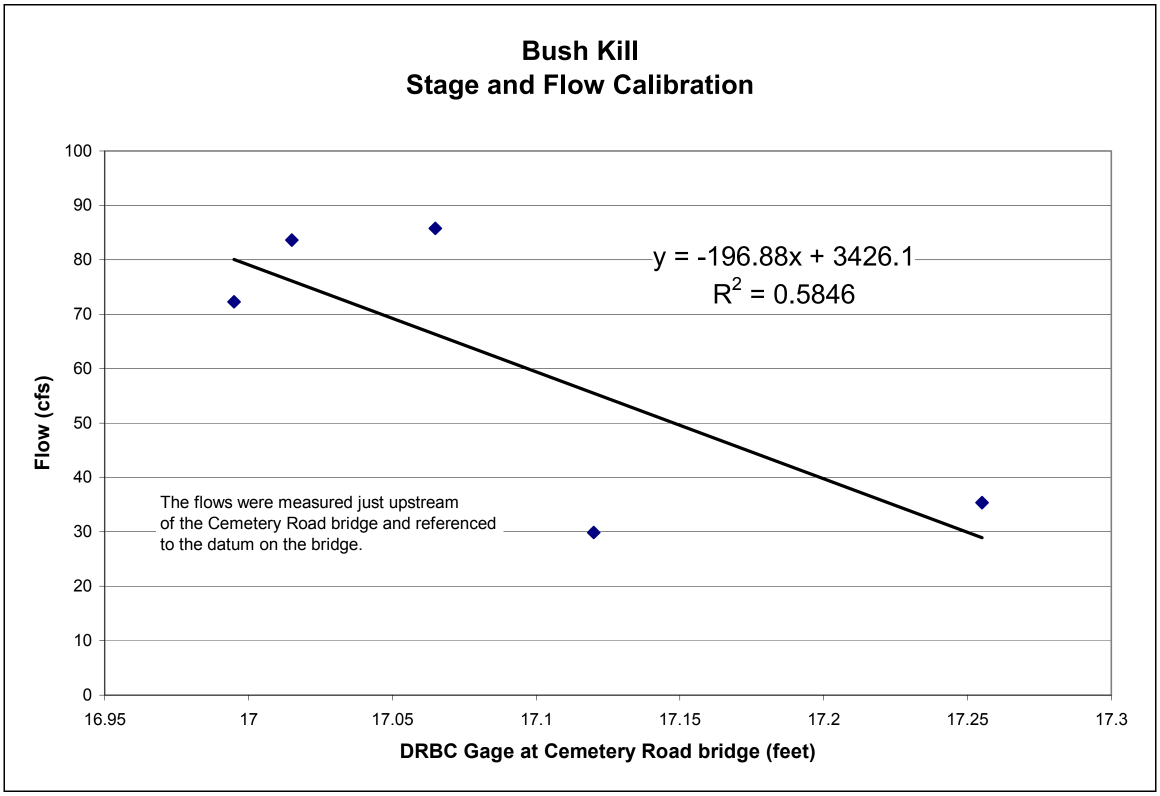

Figure 3a. DRBC stage and flow calibration for Bushkill Creek at the Cemetery Road Bridge, at river mile 184.1.

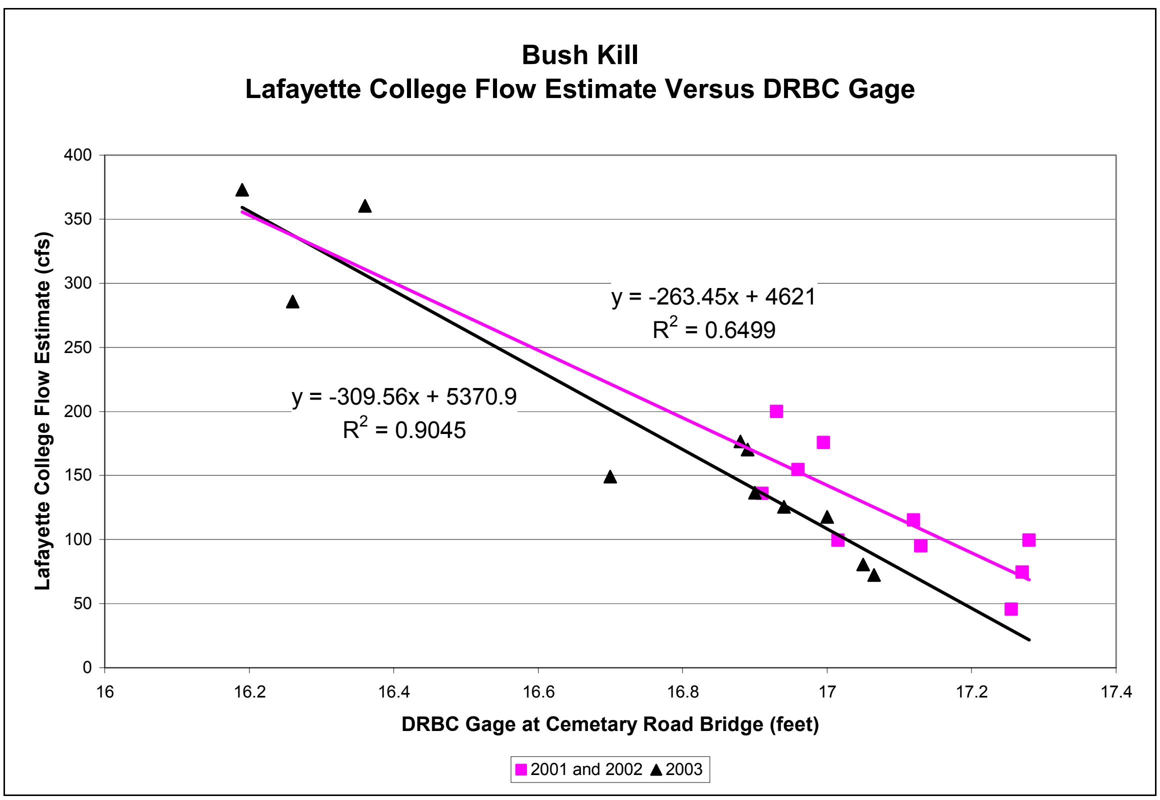

Figure 3b. Relationship between the Lafayette College flow estimates on the Bush Kill to the DRBC gage readings at the Cemetery Bridge.

Pohatcong Creek

A good relation was established at the Pohatcong Creek monitoring site for stage and flow as presented in **Figure 4**.

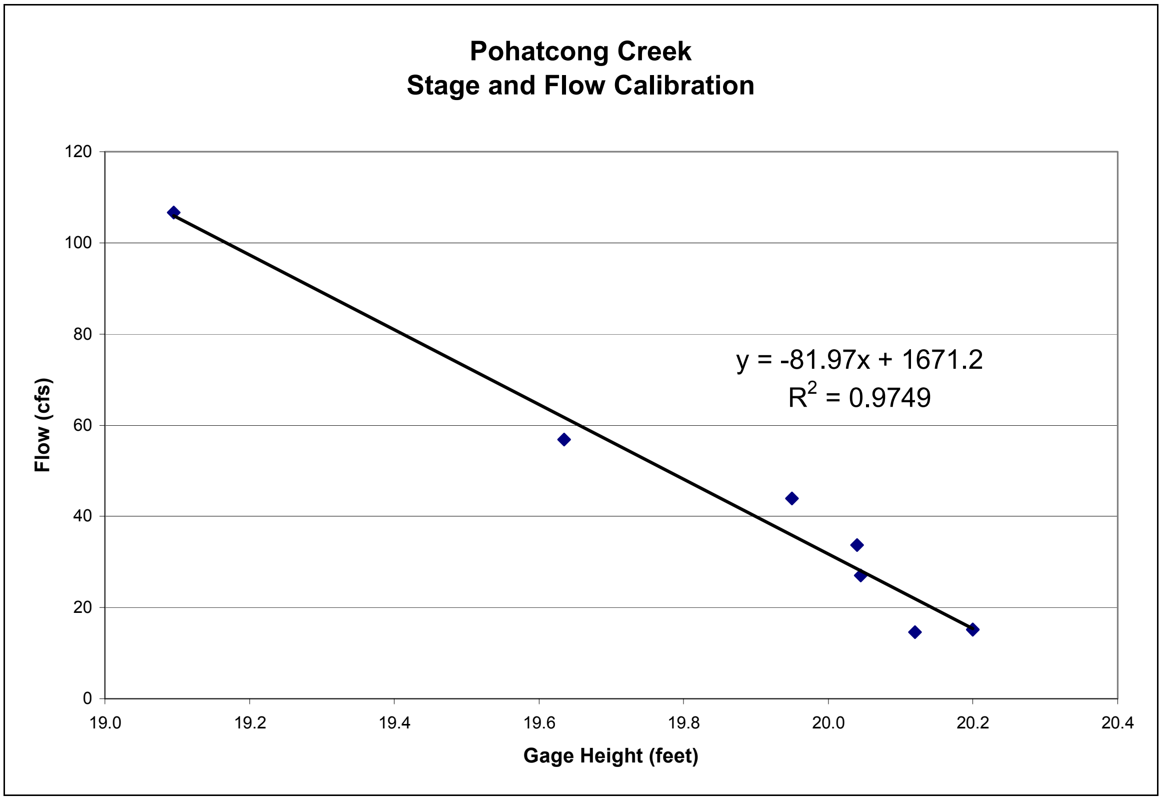

Figure 4. Stage and flow calibration for Pohatcong Creek at river mile 177.4.

Cooks Creek

Cooks Creek had a stable channel that provided a good stage and flow relationship. Since a USGS flow measurement station was located at this site, the USGS flow rating was transferred to the DRBC gage. This was accomplished by first developing the USGS flow rating (**Figure 5a**) and then determining the relationship between the USGS gage and the DRBC gage (**Figure 5b**). These both presented good associations that were then used to develop the flow rating between the DRBC gage and the USGS flows (**Figure 5c**).

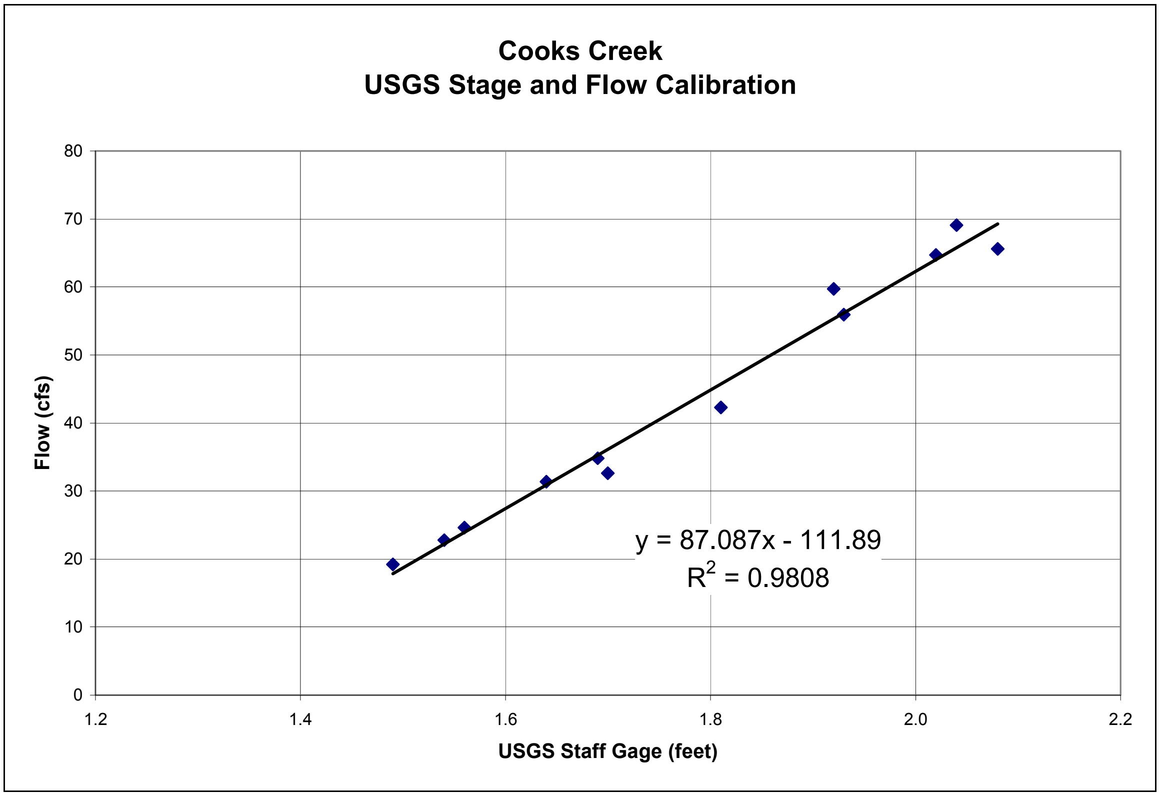

Figure 5a. USGS stage and flow calibration for Cooks Creek at river mile 173.7.

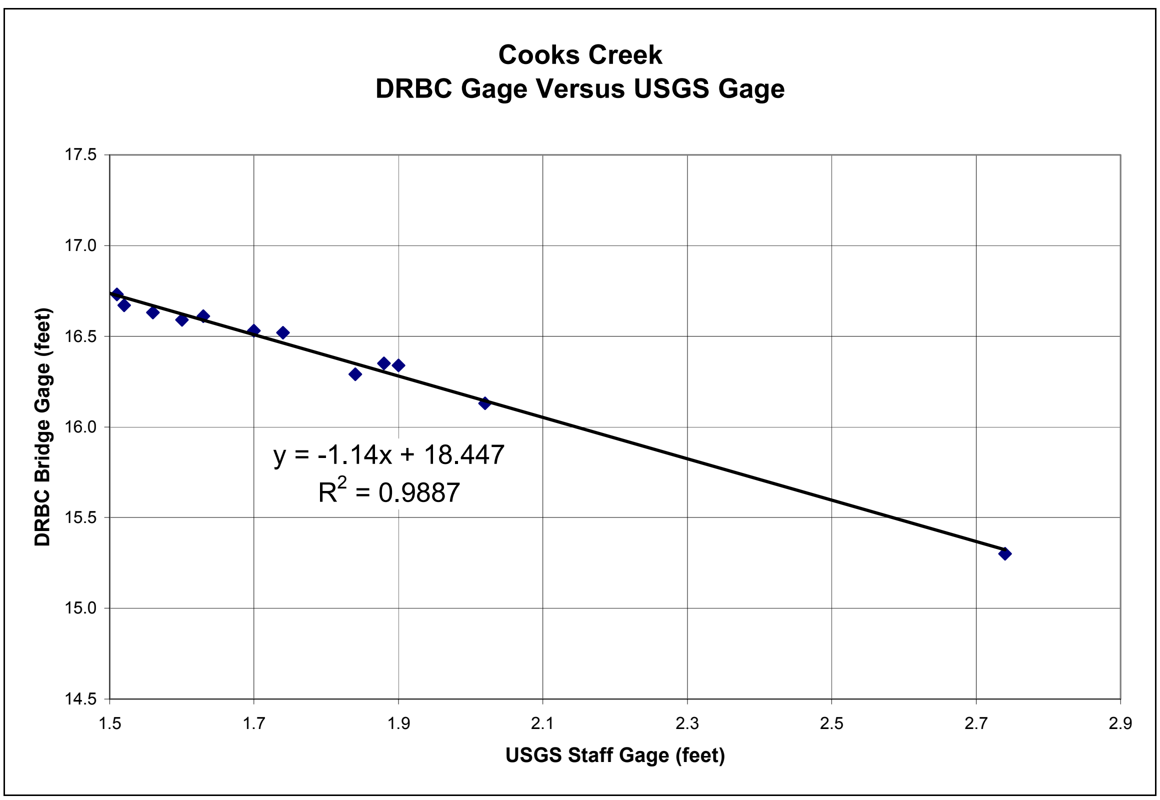

Figure 5b. DRBC bridge gage relationship to the USGS staff gage on Cooks Creek.

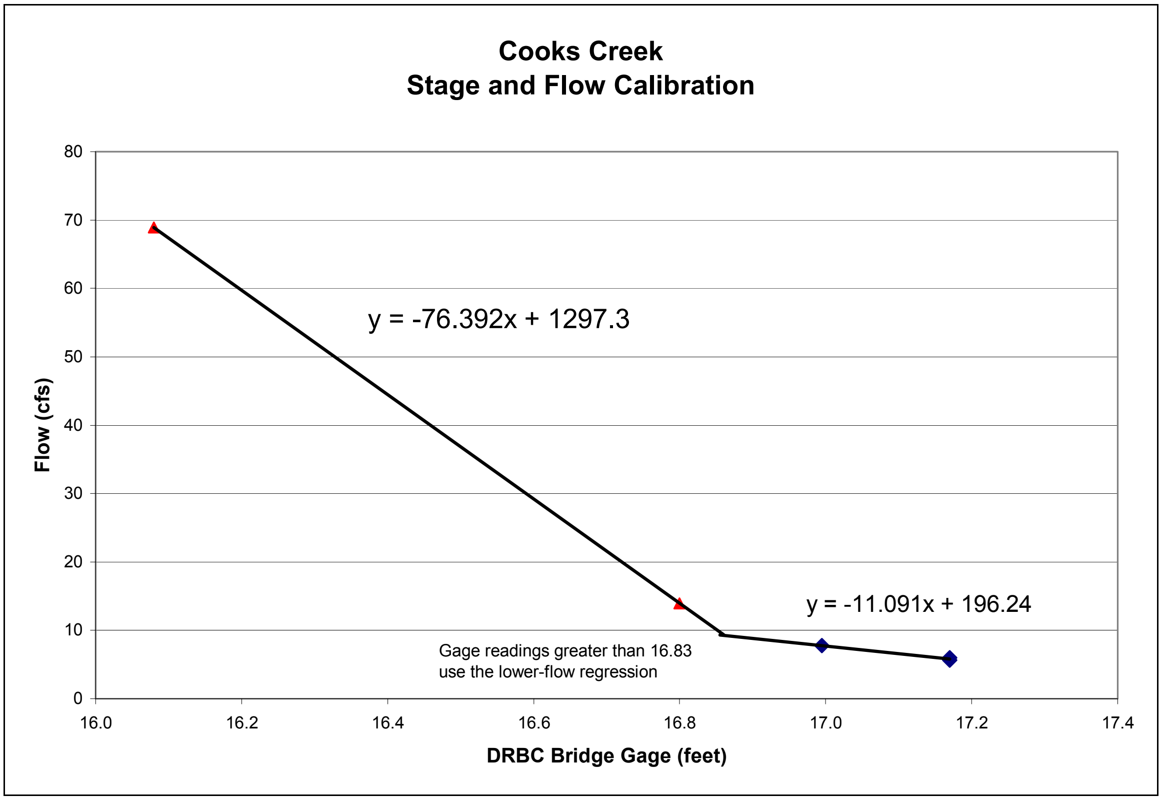

Figure 5c. DRBC stage and flow calibration for Cooks Creek at river mile 173.7.

Nishisakawick Creek

The flow measurement site for Nishisakawick Creek was located in a pooled area just upstream of the Route 12 Bridge. The stream channel was reconfigured by several large storm events. **Figure 6** shows a shift in the stage and discharge relationship for Nishisakawick Creek between the combined 2001 and 2002 data and the 2003 data. Additional stage and flow data were available from a USGS flow measurement station, located approximately 2 miles upstream from the mouth. However, only one comparison had been recorded of the USGS gage and the DRBC gage. Dual measurements need to be obtained between the USGS gage and the DRBC gage to determine if there exists a good relationship between the two stage references. If a good relationship exists, then the data sets can be combined to strengthen the stage-discharge relationship.

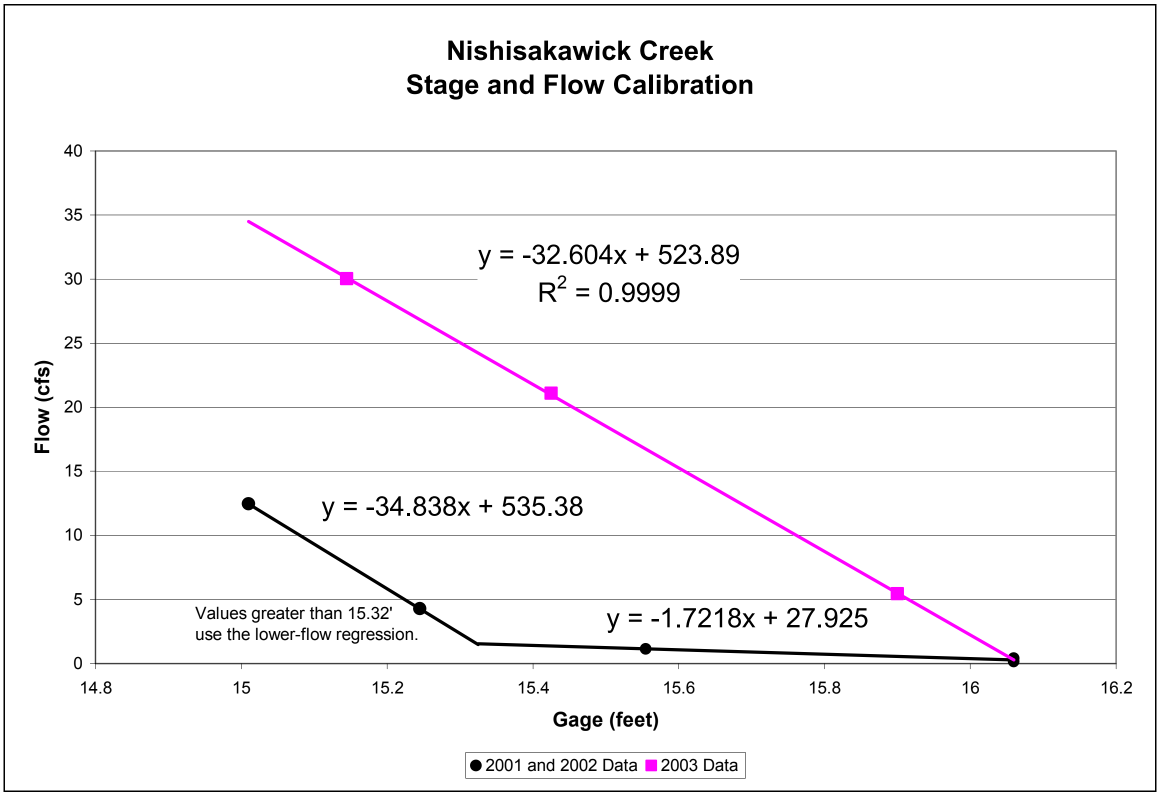

Figure 6. Stage and flow calibration for Nishisakawick Creek at river mile 164.1.

Tinicum Creek

A good relationship existed between the water stage and flow at the Tinicum Creek monitoring site (**Figure 7**). However, two of the flow measurements were approximately 15 to 20 cfs away from the linear regression line. The channel was very stable since it consisted primarily of bedrock. Therefore, the two flow measurements may have been offset from the data grouping due to backwater from the Delaware River during higher river flows.

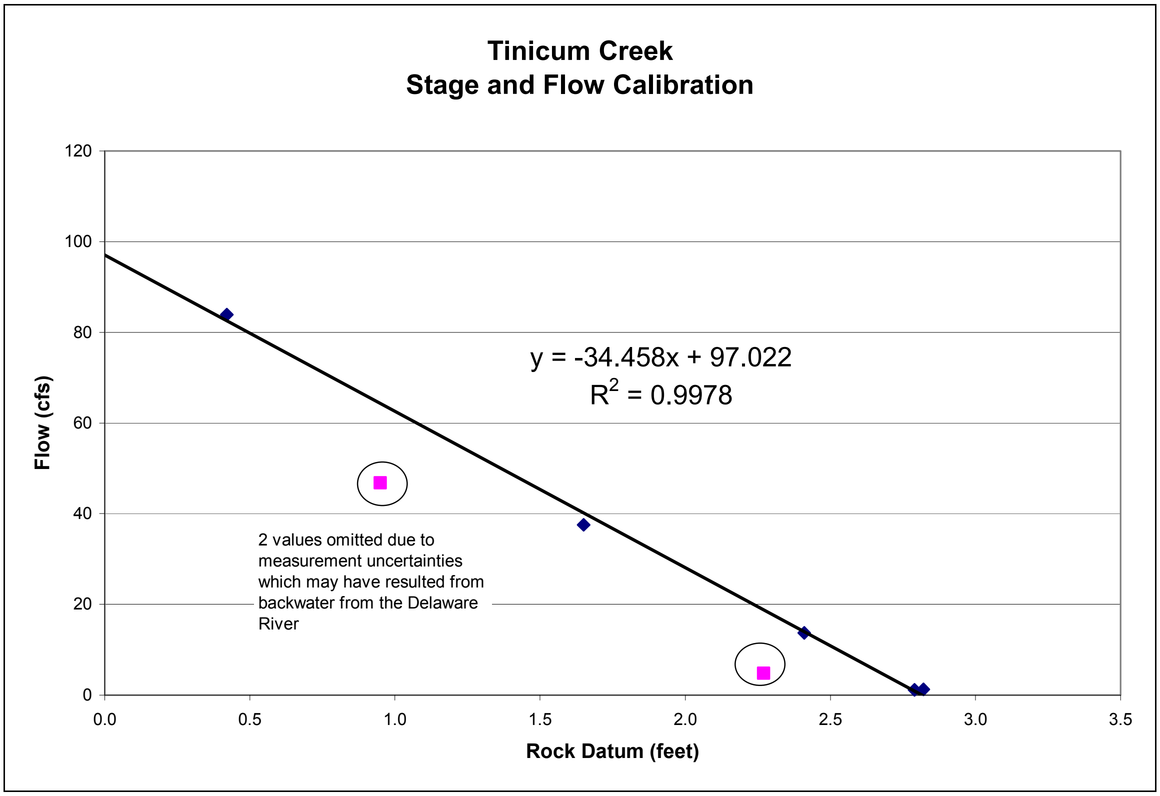

Figure 7. Stage and flow calibration for Tinicum Creek at river mile 161.6.

Tohickon Creek

Tohickon Creek exhibited a very unstable channel that required the gage to be relocated three times over three years. The most recent gage datum was located on the wing wall of the aqueduct over the Tohickon Creek. Although this site was not as accessible as the first two sites, the channel was more stable. A USGS flow measurement station was located approximately eight miles upstream from the DRBC site. There existed a good relationship between these two gages for flows up to approximately 45 cfs, after which the correlation became very weak. Therefore, the DRBC stage and flow rating was used independently of the USGS data. **Figure 8** shows the Tohickon Creek rating curve.

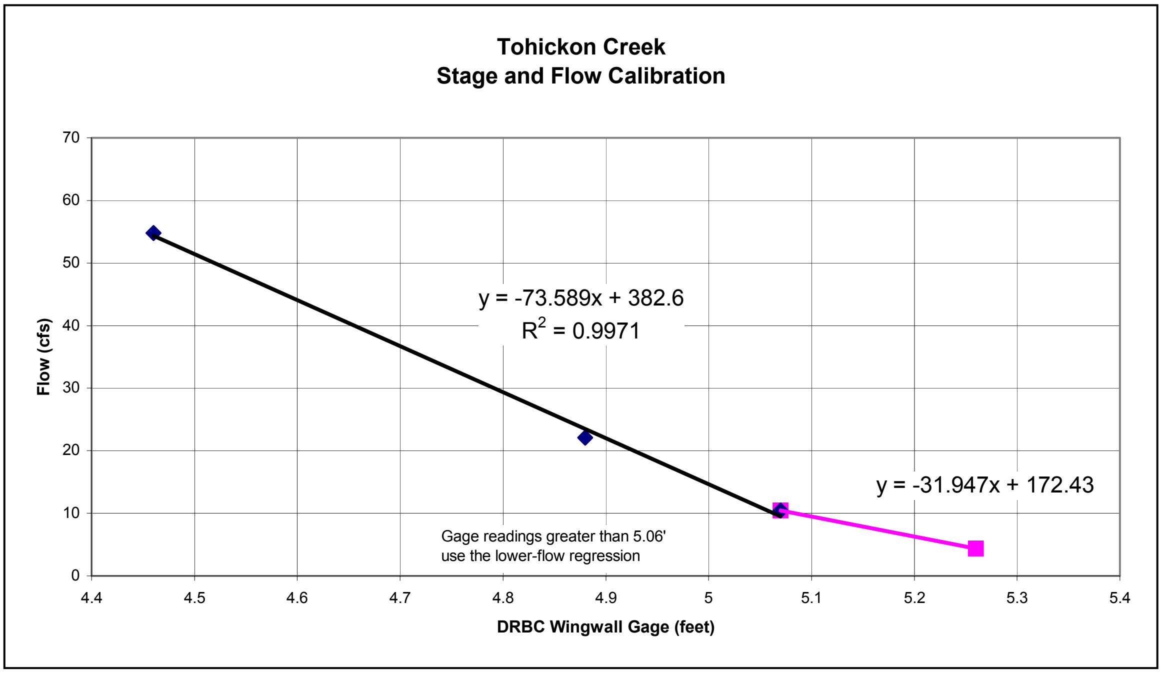

Figure 8. Stage and discharge calibration for Tohickon Creek at river mile 157.0.

Paunacussing Creek

The Paunacussing Creek channel at the Route 32 site has changed several times since the first flow measurement was performed in 2001. Scouring and deposition of the unstable sediments as well as the construction of a new bridge and abutments has required the recalibration of the flow rating many times. In 2003, the bridge datum was supplemented with a rod (staff) gage, located approximately 30 feet upstream of the bridge. This gage has shown to be stable except for an initial settling of the rod just after installation. **Figures 9a and 9b** present the stage and flow calibrations for the rod and bridge gages, respectively.

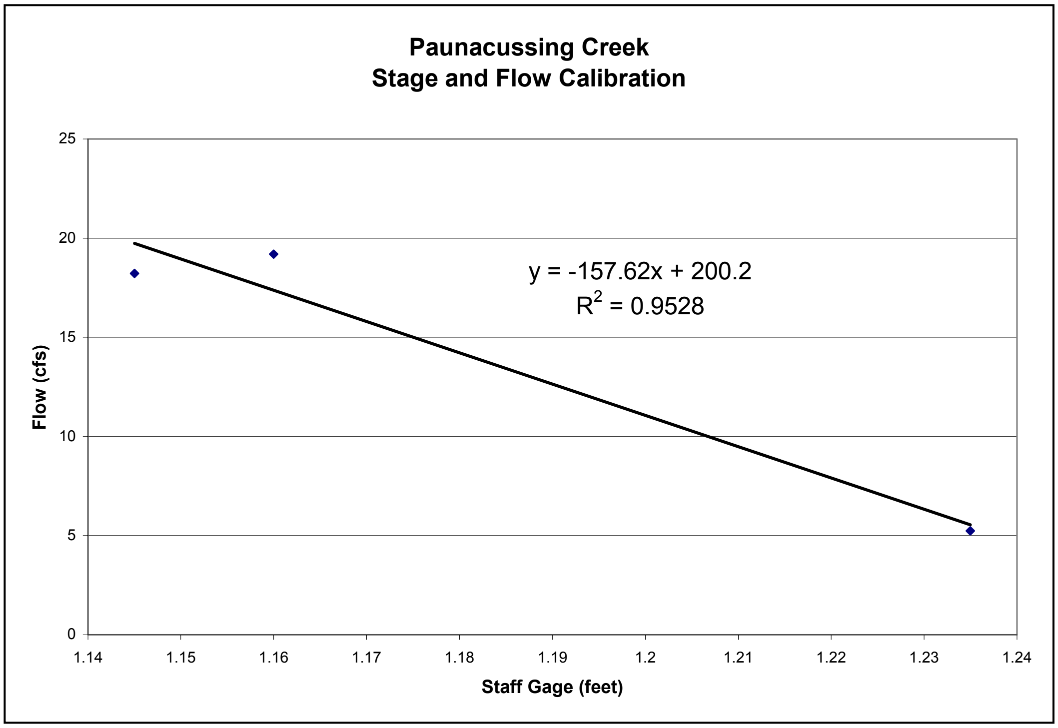

Figure 9a. Staff gage and flow calibration for Paunacussing Creek at river mile 155.6.

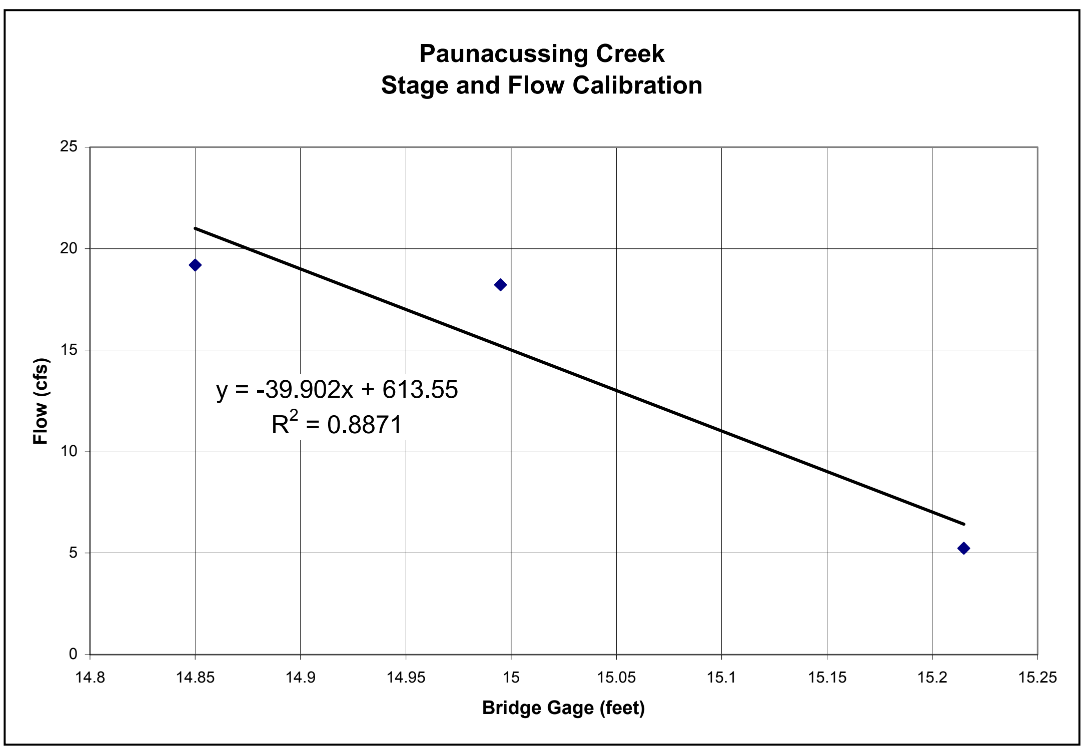

Figure 9b. Bridge gage and flow calibration for Paunacussing Creek at river mile 155.6.

Lockatong Creek

The Lockatong Creek gage has remained stable since it was first used in 2000. This site is approximately 1 mile upstream from the mouth of Lockatong Creek. The rating curve for this station is shown in **Figure 10a**. A USGS flow-monitoring site was located near the mouth. The USGS flow rating presented an unusual flow versus stage relationship. Therefore, in this case, the DRBC flow rating did not use the USGS data as a supplement. **Figure 10b** illustrates the USGS flow-rating curve for the Lockatong Creek at the route 29 bridge.

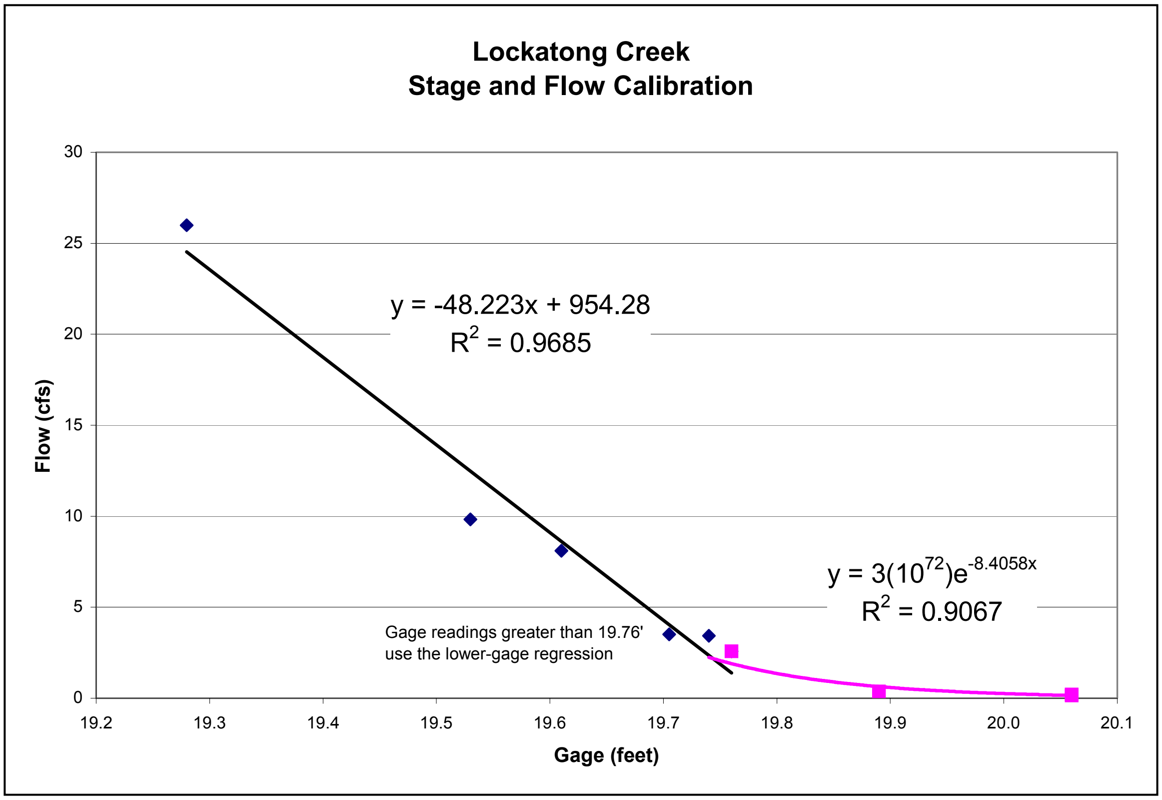

Figure 10a. Dual stage and flow calibrations for Lockatong Creek at river mile 154.0.

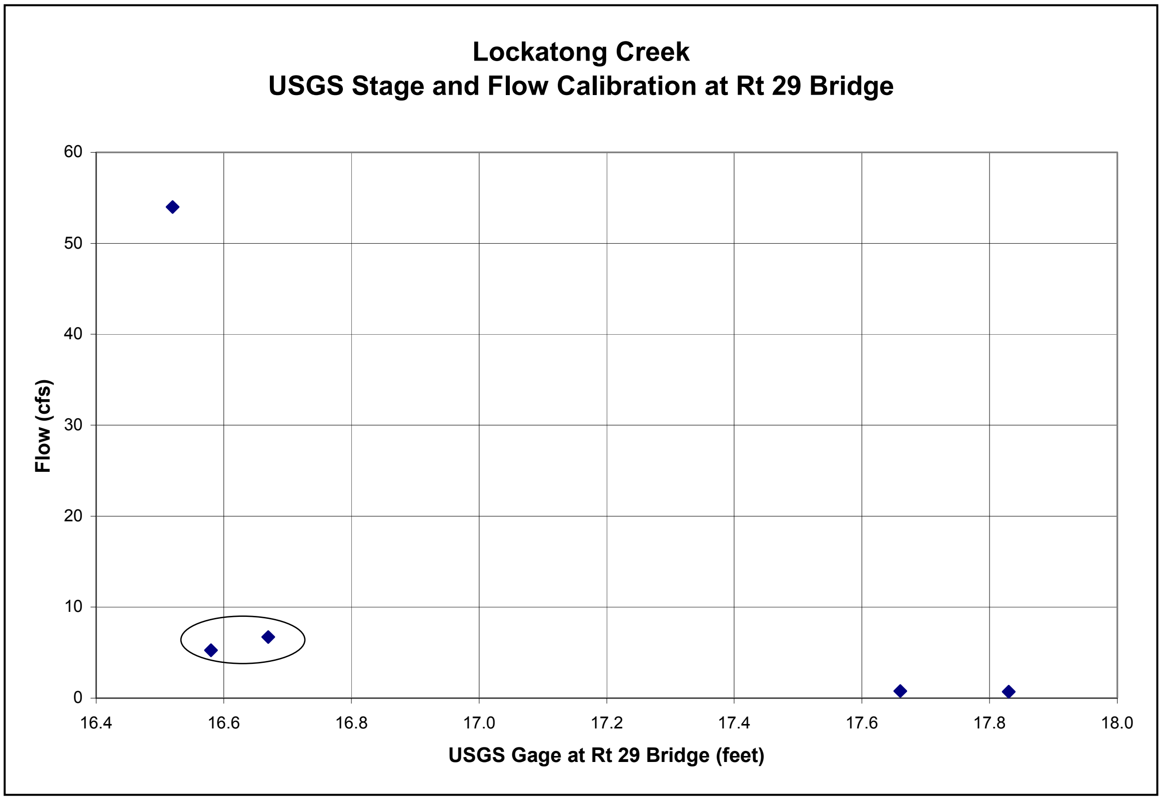

Figure 10b. USGS stage and flow calibration for Lockatong Creek at the route 29 bridge.

Wickecheoke Creek

The DRBC flow-monitoring site was located at the Route 29 Bridge, approximately a quarter mile upstream of the mouth. This site presented a stable relationship between stage and flow due to the bedrock substrate. The USGS also had a flow-monitoring site at a covered bridge that was approximately 2 miles upstream of this site. The stage and flow data from this site presented a good flow rating. Therefore, the USGS data were included in the DRBC flow rating as presented in **Figure 11a**. The USGS flow rating is presented in **Figure 11b** and the DRBC versus USGS stage measurement comparison is shown in **Figure 11c**. These relationships were used to develop the DRBC flow rating.

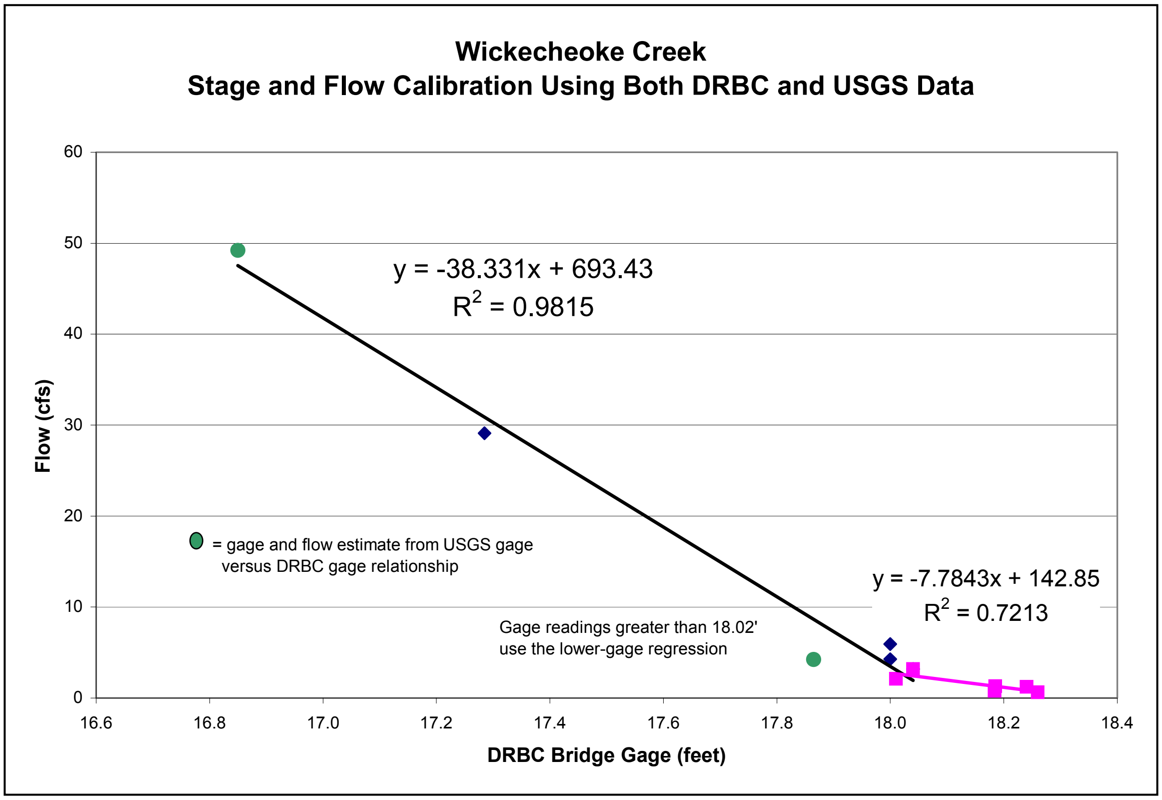

Figure 11a. Stage and flow calibrations for Wickecheoke Creek at river mile 152.5.

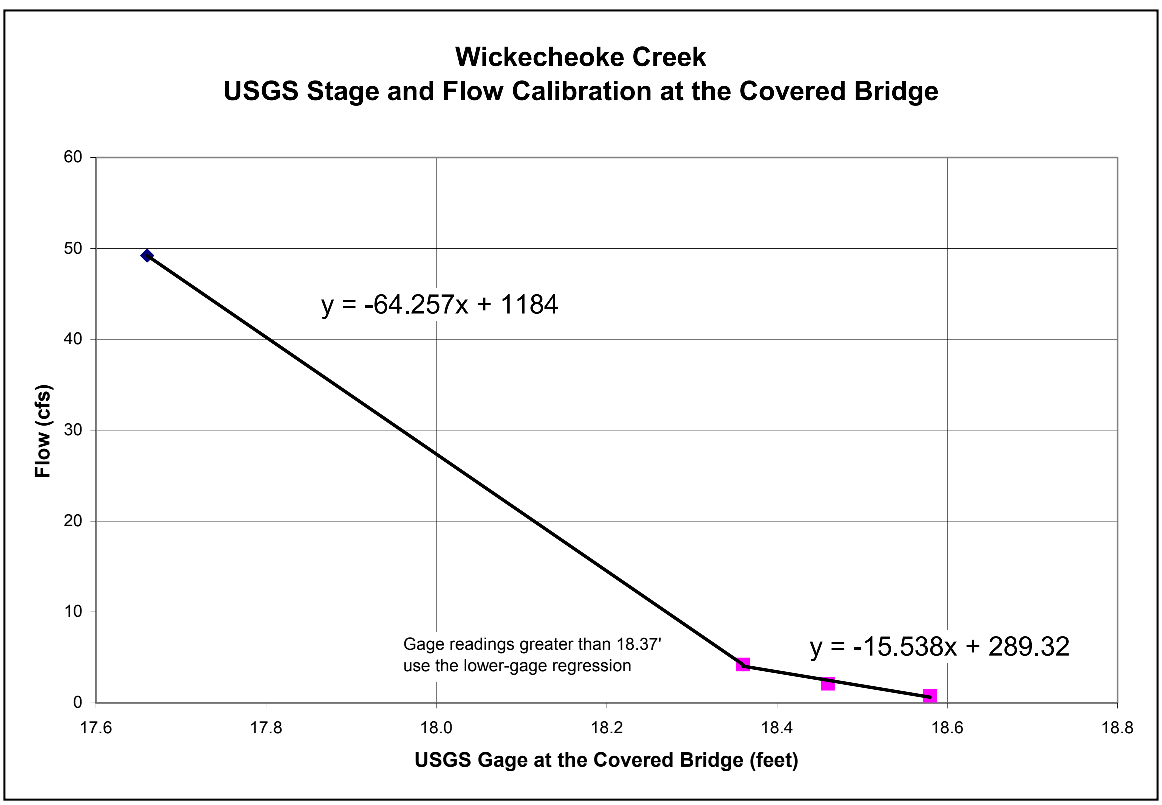

Figure 11b. USGS stage and flow calibration for Wickecheoke Creek at the covered bridge.

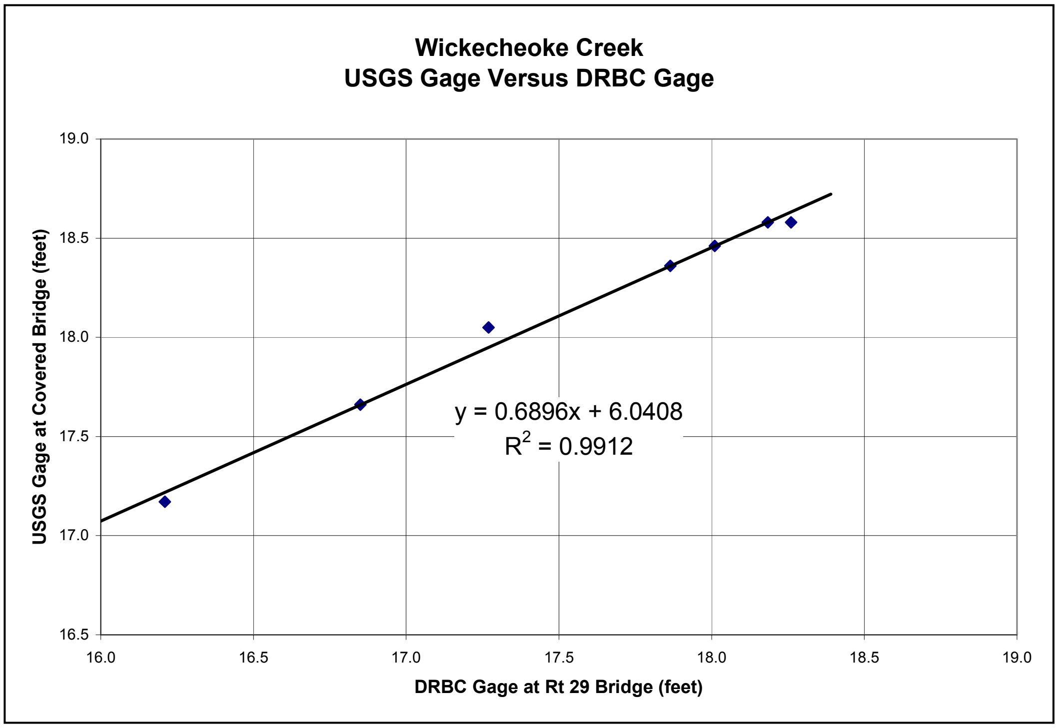

Figure 11c. USGS and DRBC stage relationship for Wickecheoke Creek.

Pidcock Creek

Pidcock Creek has shown a good stage and flow association since its initiation in 1998. This rating is presented in **Figure 12**.

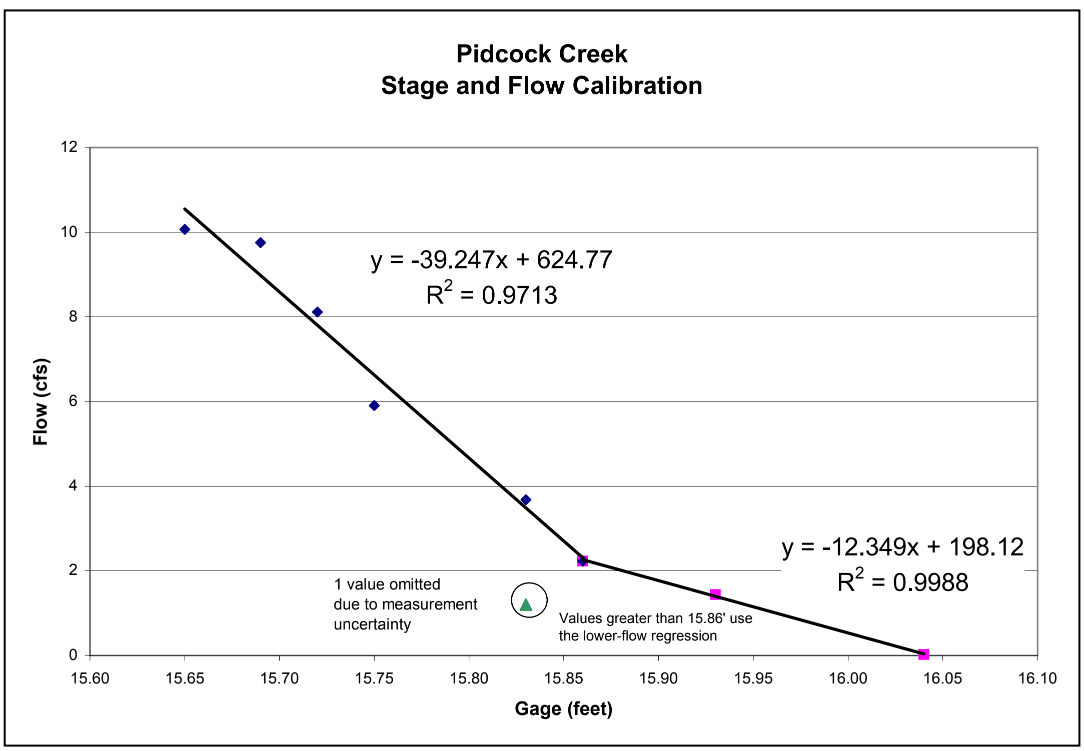

Figure 12. Stage and flow calibrations for Pidcock Creek at river mile 146.3.

Continuous Flow Monitoring as of March 25, 2004

USGS flow data were available as a continuous record for Tohickon Creek, Lehigh River, and the Musconetcong River. The records for the Lehigh River and Musconetcong River were transferred to the DRBC sampling site near the mouth of these streams by using the ratio of the drainage areas (drainage-area-weighting).

Continuous flow monitoring was used to determine: 1) hydrologic associations of streams without USGS flow gages to nearby USGS flow measurement stations; 2) areas (watersheds) with similar precipitation events; 3) flow-related fluctuations in water quality; and 4) estimates of temporal pollutant loading. Comparing the characteristics of hydrographs for the timing and duration of runoff events can identify areas exhibiting similar precipitation patterns. The timing and magnitude of runoff for peak flow and the trailing edge (base flow) may be associated with soil type and depth, karst conditions, and/or land use. Water quality samples that were collected near the flow monitors could be directly associated with the hydrograph (i.e., leading edge, peak, trailing edge, or base flow) to facilitate the assessment of unusual fluctuations in water quality.

Two pressure transducers were installed in neighboring watersheds during 2002 that drained to the Delaware River. One was placed near the mouth of Lockatong Creek and one was positioned near the mouth of Wickecheoke Creek. Both watersheds were located in Hunterdon County, New Jersey. Flow measurements were performed near the monitors and associated with the water depth as measured by the pressure transducers to calibrate flow with water depth. Using this association, continuous water stage measurements provided a continuous flow record.

The watersheds were similar in size: 23.2 and 26.6 square miles for the Lockatong and Wickecheoke Creeks, respectively, and had geological foundations of shallow soils with hard shale (argillite, Brunswick, “mud rock,” and some diabase) bedrock. Similar sized watersheds with similar geology should show similar runoff characteristics. **Figure 13** shows the relationship between the hydrographs from May through October 2002 and the timing of water quality sampling.

The peak flows near the mouth of each stream were constantly within 2 hours of each other, with a minimum lag time of 0.67 hour. However, when compared to the USGS flow data from the Tohickon Creek, peak flows were usually off by 4 or more hours. The Tohickon Creek gage is located nearby on the Pennsylvania side of the Delaware River.

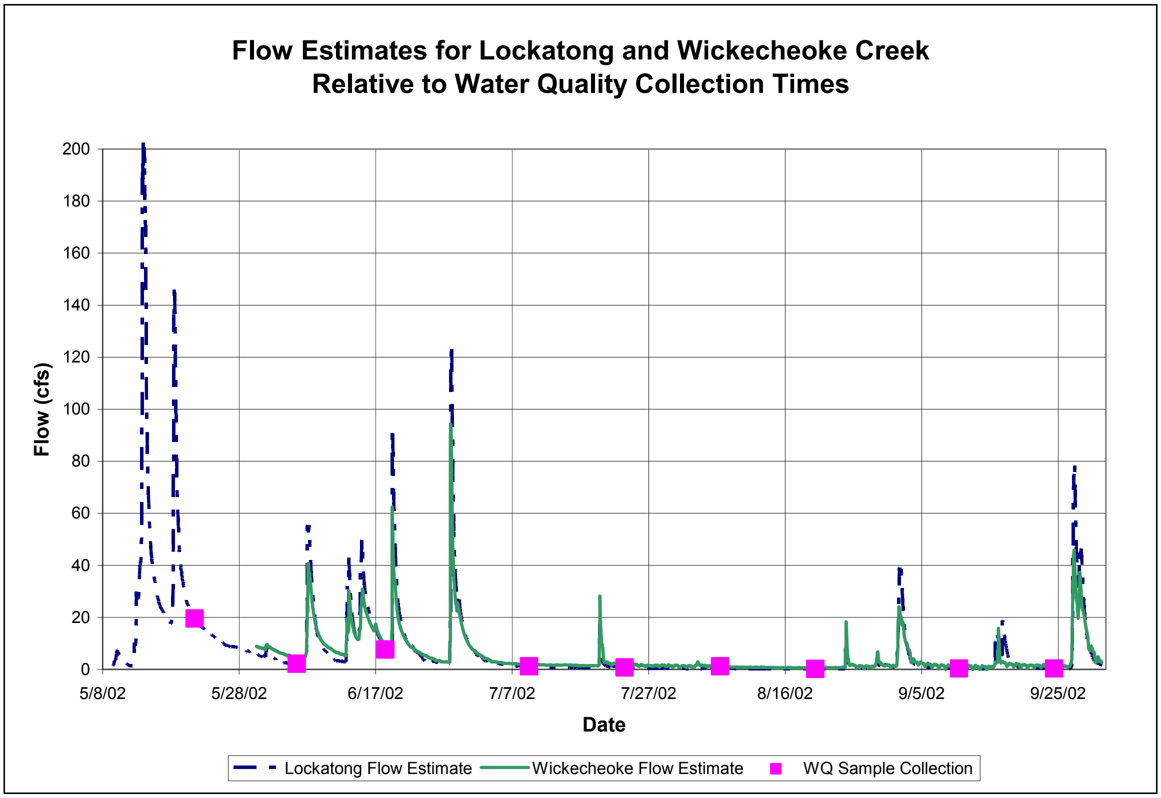

Figure 13. Comparison of runoff hydrographs for Lockatong and Wickecheoke Creeks and the associated flows during water quality sample collections.